



## Effect of process parameters on pelletisation of herbaceous crops

P. Gilbert<sup>a,b</sup>, C. Ryu<sup>c,\*</sup>, V. Sharifi<sup>a</sup>, J. Swithenbank<sup>a</sup>

<sup>a</sup> Department of Chemical and Process Engineering, Sheffield University, Sheffield S1 3JD, UK

<sup>b</sup> Tyndall Centre, Department of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester M60 1QD, UK

<sup>c</sup> School of Mechanical Engineering, Sungkyunkwan University, Suwon 440-746, Republic of Korea

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### ABSTRACT

Straw, sawdust and other herbaceous crops benefit from pelletisation, as the process increases the materials bulk density therefore reducing transportation and storage costs; providing better material feeding with less dust formation. This study investigated a pressure pelletisation method of switchgrass for five types of material preparation: raw cut switchgrass, raw shredded switchgrass, torrefied switchgrass, switchgrass combined with heavy pyrolysis oil and wheat straw. The effects of pelletisation pressure and temperature on the quality of pellets were evaluated in terms of density, mechanical strength and durability. Temperature had a greater effect than pressure on pellet quality, where at elevated temperatures, the lignin present in the biomass softened and acted as a binding agent. The cut switchgrass produced more desirable pellets over shredded switchgrass due to an additional binding effect of intertwined fibres. The torrefaction of grass was not an attractive pre-process as the pellets were very brittle and possessed little mechanical strength and reduced bulk density. At elevated temperatures, with a grass to tar ratio of 2:1, the pellets were twice as strong as pellets made by cut switchgrass. The increased durability was a result of lignin present in the biomass and the heavy oil dispersing inside the pelletiser, which filled in the gaps between the switchgrass fibres upon heating. Finally, the pellets were burnt in a fixed bed combustor and the ignition rate and average burning rates were evaluated. The results have provided an indication to how the pellets would perform compared to other fuels. Future work should focus on the standardisation of herbaceous crop pelletisation and in particular, upper and lower bound limits for the moisture content should be investigated, as moisture was found to have a significant impact on pellet quality.

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### 1. Introduction

Pelletisation of biomass is a mass and energy densification for materials that possess low bulk densities such as sawdust, straw and other herbaceous energy crops. The typical bulk density of biomass chips is less than  $150 \text{ kg/m}^3$  while that of wood pellets is typically over  $600 \text{ kg/m}^3$ . The process reduces transportation costs and provides better handling and feeding of the biomass with less dust formation. For energy crops that are harvested only for a few weeks of a year, the process also provides potential storage for off-season utilisation.

In general, the pellet quality depends on the properties of the feedstock – in terms of biomass type, moisture content and particle/fibre size; and quality management of the manufacturing process – in terms of operating conditions, pelletiser type and binding agent. Much attention has been focused on wood pellets, where wood pelletisation is already a reputable technology [1–7]. Research at the Swedish University of Agricultural Sciences

has tested nine different pellets from various sources [3]. The pellets from bark had the highest durability whereas the conventional sawdust pellets had the least. Pellet density was found to have no effect on durability. In a similar pilot study to the above, the same nine pellet samples were stored for five months in plastic bags in an unheated barn to examine the changes in moisture content, heating value and ash content [4]. The research concluded that storage of the pellets led to a negative effect on durability, especially on pellets made from fresh materials. In general, the changes in pellet quality during storage in large bags were not large, but notable. Li and Liu [2] studied the effects of pelletisation conditions for large wood residue pellets (logs) made using a simple compression rig. The analysis concluded that moisture content in the range of 5–12% produced good quality wood-based logs. For sawdust, compaction pressures of 100 MPa produced a good log however, even pressures of up to 138 MPa failed to produce adequate logs when using wood chip based fuel.

Studies on pelletisation of other biomass materials have been also reported in literature. Mani et al. [8] examined the density of pellets from grasses under different compressive forces, particle sizes and moisture content using a roller-die pelletiser, and devel-

\* Corresponding author. Tel.: +82 31 299 4841; fax: +82 31 290 5889.

E-mail address: [cryu@me.skku.ac.kr](mailto:cryu@me.skku.ac.kr) (C. Ryu).

oped a linear model for the relation of asymptotic modulus and maximum compressive force. Optimal conditions for pellet production from reed canary grass have been studied [9]. Continuous operation for shredded grass in a roller-die requires a minimum moisture content of 13.8% to produce high density and durability pellets. The effects of moisture content and compression pressures on the pelletisation of coal tailings and spent mushroom compost has been assessed using a simple cylindrical compaction machine [10]. Too dry particles become hard while losing the plasticity, which increases the friction between particles that partially consumes the compression energy applied. The pellets from wet particles also had much lower tensile strength since the excess water wastes the compression energy and the voids filled with water loosen the cohesion of particles. The ideal value of moisture content was about 10% in the materials, for which the pellets had a three times higher tensile strength compared to that from materials with 2% of moisture content. Another study also reported that, if the biomass is too wet, the pressure required for pelletisation has also been reported to increase dramatically [11].

Considering that wood pellets from forestry residues already has successfully established technologies and markets for production and consumption in some European countries, dedicated studies on the pelletisation of herbaceous crops has a great potential to make them more competent as an energy source. This study investigates the effects of pelletisation conditions on product properties for switchgrass and wheat straw using a simple compression rig. The pellets produced from different pre-processing (shredding, torrefaction and mixing with heavy pyrolysis oil), pressure (up to 552 bar) and temperature (up to 125 °C) were examined in terms of pellet density, compressive strength and durability. The combustion of the pellets were also tested in a fixed bed reactor under typical operating conditions and compared to that of raw grass presented in Khor et al.'s study [12].

## 2. Materials and methods

### 2.1. Material properties and pre-processing

The grass samples were supplied by Rothamsted Research, UK, and were harvested in 2004. After harvest, the biomass was dried in covered storage for 2 months, where the moisture content decreased to 30% or below. In this study, further pre-drying was achieved through storing the biomass in bags in a cool dry place in the laboratory, which reduced the switchgrass moisture content to approximately 6.5%. Pre-drying would increase the process costs however, if small-scale CHP is assumed, process heat would be used to pre-dry the biomass before pelletisation. At the time of pelletisation, no degradation was observed in the switchgrass. From different pre-processing, four types of switchgrass were prepared: raw long-cut switchgrass (10–70 mm long), raw shredded switchgrass (0–4 mm long), torrefied switchgrass and raw grass mixed with heavy pyrolysis oil. The properties of the fuels are presented in Table 1.

Torrefaction of biomass is pyrolysis at low temperature (200–300 °C), which increases the calorific value of the products and reduces the moisture content. Torrefied switchgrass was prepared using a fixed bed pyrolyser at final temperatures of around 250 °C with a heating rate of 10 °C/min. Details of the pyrolyser is given elsewhere [13]. After torrefaction, the mass yield of the solid was 72% while containing 84% of energy content of the raw material. Such results compare well to the literature [14–17].

Addition of heavy pyrolysis oil to the grass was also tested. Due to polymerisation reactions that slowly take place during storage of pyrolysis oil, the heavy fraction in the liquids produces water and gets more viscous [18]. Although this is not desirable for han-

**Table 1**

Fuel properties of test materials.

| Material                        | Raw switchgrass <sup>b</sup> | Torrefied switchgrass | Wheat straw <sup>b</sup> | Heavy pyrolysis oil |
|---------------------------------|------------------------------|-----------------------|--------------------------|---------------------|
| <i>Proximate analysis (%wt)</i> |                              |                       |                          |                     |
| Moisture                        | 6.43                         | 3.70                  | 7.88                     | –                   |
| Volatile matter <sup>a</sup>    | 82.84                        | 70.66                 | 80.08                    | 79.44 <sup>c</sup>  |
| Fixed carbon                    | 7.24                         | 20.84                 | 6.76                     | 19.68               |
| Ash                             | 3.49                         | 4.80                  | 5.28                     | 0.88                |
| <i>Ultimate analysis (%daf)</i> |                              |                       |                          |                     |
| C                               | 48.33                        | 53.37                 | 50.18                    | 66.05               |
| H                               | 6.07                         | 5.92                  | 6.31                     | 6.72                |
| N                               | 0.48                         | 0.87                  | 0.69                     | 0.71                |
| S                               | 0.57                         | 0.70                  | 0.44                     | 0.00                |
| O <sup>a</sup>                  | 44.55                        | 39.14                 | 42.38                    | 26.52               |
| Gross calorific value (MJ/kg)   | 17.3                         | 20.6                  | 16.4                     | 25.8                |

<sup>a</sup> By difference.

<sup>b</sup> Khor et al. [12].

<sup>c</sup> Including moisture.

dling and atomisation of the oil, the heavy oil has much higher calorific value (25 MJ/kg) than fresh pyrolysis oil (~15 MJ/kg). Using the heavy oil for pelletisation can be advantageous due to increased calorific value and the binding effect for strong and durable pellets. Although the health and safety issues for the pellets containing the pyrolysis oil require further investigation, this can be an additional route for the use of pyrolysis products. The heavy pyrolysis oil used in this study was acquired from pyrolysis liquids of shredded wood stored for several months. The switchgrass pellets were also compared to wheat straw pellets manufactured and tested using the same techniques.

### 2.2. Pelletiser setup

Although there is a lot of variation between pelletisers, the typical method for mass production is to use a die and press roller [1]. For laboratory-based small-scale work, pelletisers are often much more simplistic in design, generally consisting of modified hydraulic presses, where ease of pellet manufacture, time scale or costs would not be an issue [2]. For the purpose of studying the effects of pressure on pellet formation, testing different fuel types or analysing quality and storage capabilities, such a process would be sufficient.

Fig. 1 shows a schematic of the pelletiser used in this study. It consisted of a modified hydraulic press, a 26.8 mm diameter pellet mould and a ram, and was capable of providing up to 170 bar (2500 psi) of pressure and operating temperatures up to 300 °C. It should be noted that the pressure recorded on the pressure gauge represented the force exerted over the base of the pelletiser. In fact, a ratio factor had to be introduced, as the pressure exerted on the pellet would have been far greater since the pelletiser diameter was 26.8 mm. The factor between the two surface areas was approximately 4.06; consequently, a reading of 170 bar on the pressure gauge translated to a pressure of 690 bar being exerted on the pelletiser ram. Eight grams of material could be loaded into the pellet mould through the top, which produced a 20–31 mm long pellet depending on its density. A thermocouple placed into the bed ensured the temperature reached the desired value. After reaching the required pressure, the pellets were held there for 30 seconds before the pressure was released. Research found that by increasing the holding time for durations longer than 20 seconds had little effect on pellet density [2]. The pelletiser pressure was varied from 55.2 bar (812 psi) to 552.3 bar (8120 psi) in steps of 812 psi. For the pellets formed at elevated temperatures, the pressure was fixed at 165.7 bar (2436 psi) and the temperatures

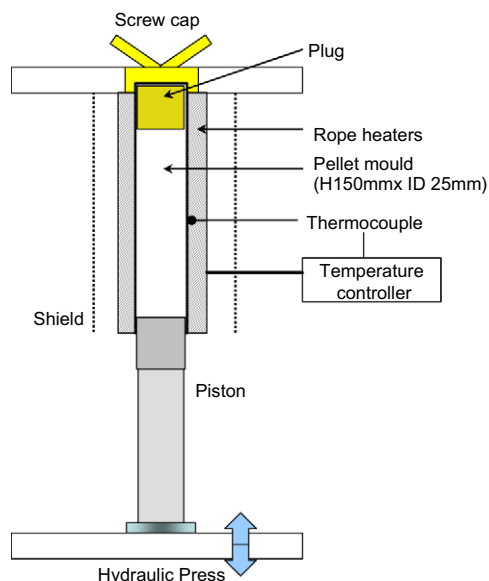


Fig. 1. Schematic of the pelletiser.

examined were 50, 75, 95 and 125 °C. Three pellets were made at each test condition and 14–17 °C was assumed the average room temperature during pelletisation.

### 2.3. Assessment of pellet quality

The effects of pelletisation pressure and temperature on the quality of pellets were evaluated in terms of density, mechanical strength and durability. The density of the pellet was calculated after the pelletisation process and again, one hour later. The bulk density was additionally calculated for the cut switchgrass case. The tensile strength of a pellet was measured using a tensometer for compression of a pellet in the radial direction [19], which is the maximum pressure a pellet can take without cracks or disintegration. The results were provided in Newton's, which could be converted into a pressure as a means of comparing pellets with different lengths and cross-sectional areas. The pellet durability was tested using a vibrating bed at a fixed frequency (5 Hz) and amplitude (7–8 mm) in order to simulate the vibration during transportation, as shown in Fig. 2. The pellets were weighed at set intervals

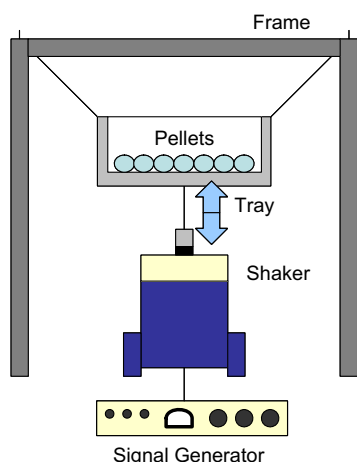


Fig. 2. Schematic of the pellet durability tester.

and a curve of mass loss against time could be produced for total duration of 100 min.

### 2.4. Dynamic mechanical thermal analysis

The effect of softening by lignin at elevated temperatures was investigated using Dynamic Mechanical Thermal Analysis (DMTA) which is widely used to measure the viscoelastic nature of polymers. A Metravib Viscoanalyser VA2000 DMTA was used for a pellet of 10 mm diameter. A temperature sweep from 25–125 °C with a ramp rate of 5 °C/min was run to log the modulus of the pellet with increasing temperature. 200 g of pre-load was put on the pellet to prevent the pellet over-expanding and breaking. The oscillating frequency was 1 Hz and the configured strain rate was  $1.5 \times 10^{-4}$ .

### 2.5. Combustion test in a fixed bed

Packed bed combustion is widely used for energy production from waste and biomass at various scales ranging from 3 kg/h pellet stoves to 10 ton/h moving bed incineration. The combustion of the grass pellets was investigated in the batch type packed bed reactor. This type of reactor has been frequently applied for fundamental studies of biomass combustion [12,20–23]. The reactor used in this study has an internal diameter of 200 mm and a height of 1500 mm. The details of the reactor can be found elsewhere [12].

The pellets of cut switchgrass were combusted for 936 kg/m<sup>2</sup> h (0.212 m/s) of primary air at which the maximum overall burning rate was achieved for the raw grass [12]. The bulk density of the pellets was 370 kg/m<sup>3</sup> and the initial bed height was 300 mm. Thermocouples were located up through the reactor to monitor the bed temperatures after the bed top was ignited by a start-up burner. Gas concentrations of CO, CO<sub>2</sub> and O<sub>2</sub> sampled using a probe located at y = 32 cm were analysed using a MGA 3000 analyser. The weight of the bed was also recorded using four load cells from which the reactor is suspended. From the test results, key combustion characteristics including burning rate can be derived and compared to the results for the raw switchgrass.

## 3. Results and discussion: pelletisation tests

### 3.1. Pellets of cut switchgrass

The objective of completing a full analysis of raw switchgrass, examining the effect of pressure and temperature on the pellets, was to set up a case scenario for ease of comparison between the different pellet types and to fully understand the effects of varying the parameters at the simplest level. Furthermore, from an industrial point of view, raw cut herbaceous crops would be far more economical to produce when compared to the preparation for the other fuels.

Pellets formed at higher pressures were found to be more uniform in shape, having defined dimensions, which were retained over time. As shown in Fig. 3, the pellet density increased from about 250 kg/m<sup>3</sup> at 55.2 bar to 720 kg/m<sup>3</sup> at 552 bar. The difference in the density between two pellets became less apparent at high pelletisation pressures. The bulk density of the pellets was up to 400 kg/m<sup>3</sup>. Although this is lower than 500–700 kg/m<sup>3</sup> of wood pellets [1], it is about six times higher than that of raw grass (55–68 kg/m<sup>3</sup>) [12].

Fig. 4 shows a clear linear relationship between tensile strength and formation pressure. Although no further increase in density was observed between 387 and 552 bar, the strength of the pellet was still found to increase. Pellets formed at 552 bar could withstand approximately 475 kPa through the radial plane. The results

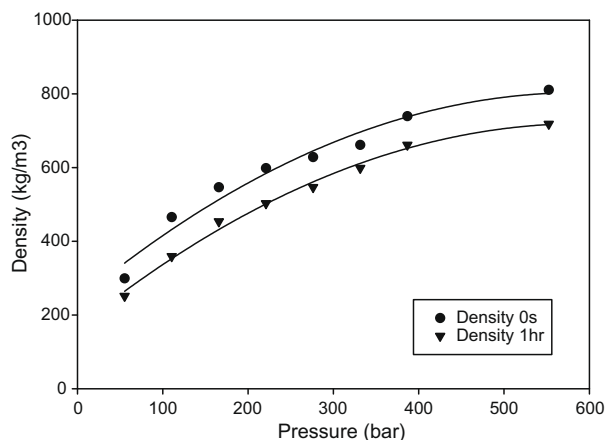


Fig. 3. Relationship between pellet density and formation pressure for cut switchgrass.

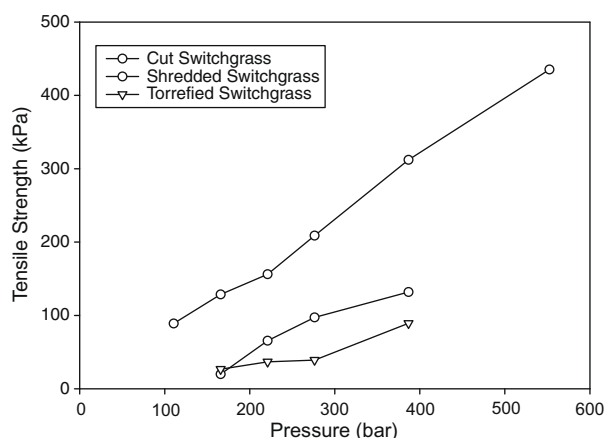


Fig. 4. Relationship between compressive strength and formation pressure for cut switchgrass.

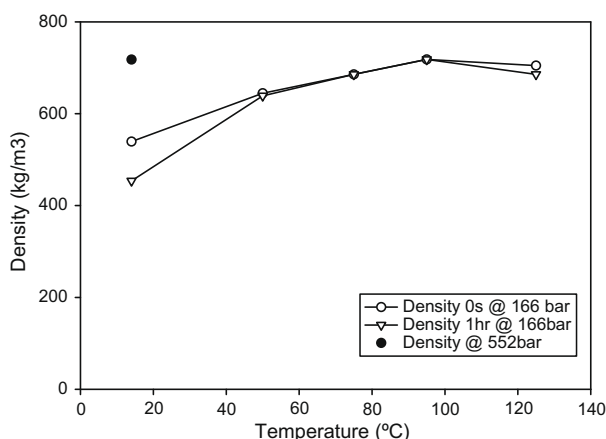


Fig. 5. Relationship between pellet density and formation temperature for cut switchgrass.

for the durability testing were very positive where a distinct, linear correlation was observed between duration time and mass loss. Over the 100 minute testing duration, a maximum of 5% material loss was observed for the 41 bar case and a 1.5% mass loss for the 552 bar case.

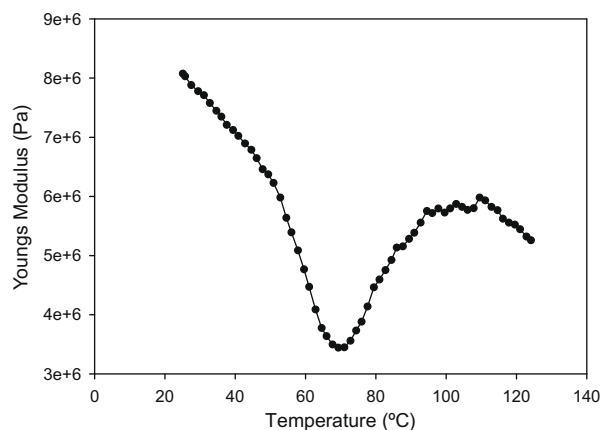


Fig. 6. Softening of switchgrass pellet acquired from dynamic mechanical thermal analysis.

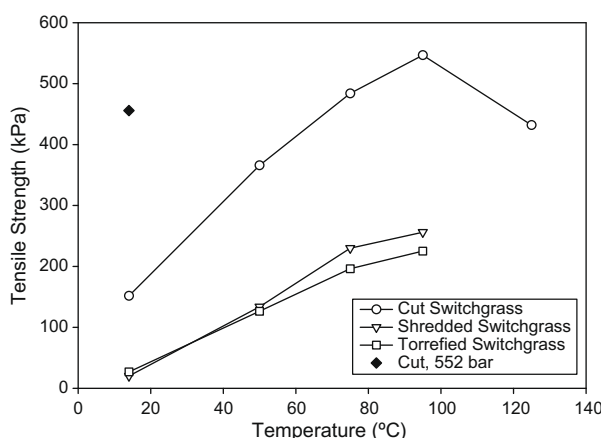


Fig. 7. Relationship between compressive strength and formation temperature for cut switchgrass.

Examining the pellets formed at elevated temperatures, the density increased substantially between 14 °C and 50 °C, as shown in Fig. 5. At 75 °C and 95 °C, the pellets did not expand at all and instead remained at the original density. From the literature [1], it was found that the natural binding material present in the switchgrass was lignin. The softening of lignin has also been reported elsewhere, where biomass was pre-heated at 50–100 °C to soften the lignin prior to pelletisation [11]. As the temperature increased within the bed, lignin softened and bound the pellets upon compression. Consequently, as the pellets were left to cool, lignin hardened again and the pellet strength increased. This binding effect explains why the pellet density does not significantly change at the 75 and 95 °C cases. The effect of lignin softening remained apparent until approximately 100 °C, where further heat addition resulted in a negative effect on pellet density. The pellets formed at 125 °C showed signs of fraying, where a small onset of abnormalities could be observed at the top of the pellet. At 125 °C, the moisture had nearly all evaporated and therefore, the liberation of water from the pellet affected the quality of the pellet.

The effect of pellet softening acquired from DMTA is shown in Fig. 6. As the temperature increases up to 70 °C, the lignin present in the pellet softens. As the temperature increases further towards 100 °C, the evaporation of moisture results in the pellet becoming harder again and more brittle, yet the modulus does not reach its original value.

The tensile strength tests shown in Fig. 7 further agreed with the theory that lignin was acting as the natural binding agent, where pellet strength was peaking at temperatures between 75–95 °C. The results suggest that between 14 °C and 75 °C a linear trend occurs, relating formation temperature and pellet strength. When the formation temperature peaked at 100 °C, any additional temperature had negative effects on the compressive strength. This was due to the lower moisture content in the pellet, which resulted in a more brittle behaviour.

### 3.2. Pellets of shredded switchgrass

The overall shape and appearance of the pellets of shredded switchgrass was much more uniform compared to those from cut switchgrass. The results for pellet density show very similar characteristics in contrast to the cut switchgrass pellets. For example, the densities were 546 kg/m<sup>3</sup> and 531 kg/m<sup>3</sup> for the cut and shredded switchgrass, respectively, 1 h after pelletisation at 276 bar and at room temperature. The tensile strength of the pellets of shredded grass is shown for various pressures and temperatures. The pellets were found to be much weaker when compared to the cut switchgrass pellets, making them completely undesirable. The reason for such high strength of the cut switchgrass pellets was the internal infrastructure of the pellet. The long strands of the cut switchgrass intertwined with each other in a pellet, which became an additional binding feature alongside the already effective lignin. At the maximum compressive pressure in the tensometer, the pellets of shredded switchgrass were found to separate through the radial plane. However, those from the cut switchgrass became oval while maintaining a pellet form.

Fig. 8 compares the durability of the pellets of the cut and shredded grass produced at elevated temperatures. The pellets made at 75 and 95 °C were seen as the strongest from above. As expected the mass loss over the 100-min period was higher – by 10% for the instance at 75 °C. By the end of the testing, one pellet had separated through the radial axis and the others were not far off. Therefore, shredding the grass is not desirable for production of strong and durable pellets.

### 3.3. Pellets of torrefied switchgrass

In this study, torrefaction was completed before the pelletisation process, where the torrefied material was cooled before pelletisation. The torrefied pellets were dark brown in appearance. The pellets were observed to be very brittle, uneven and non-homogeneous in shape. Most of the pellets manufactured sepa-

rated and broke up when handled or over-expanded through the radial plane. The tensile strength of the pellets shown in Figs. 4 and 7 was even lower than that of the shredded grass cases. The reduction in moisture and the early stages of decomposition of hemicellulose has resulted in the brittle pellet. In terms of transportation and handling abilities, the weak torrefied pellets would be undesirable, as pellet break-up could lead to blockages and severe dust formation. The potential advantage of the brittle nature, nonetheless, would be only if the end use of the torrefied grass pellets was pulverisation alongside coal. However, pelletisation could be combined with torrefaction by completing it above the hemicellulose degradation temperature. Therefore as the biomass thermally degrades, the release of pyrolysis vapour, breakdown of cellulose and softening of lignin could result in a high-quality pellet being formed. This would require further investigation and techno-economic analysis of both options for torrefaction should be completed.

### 3.4. Pellets of mixed switchgrass/heavy pyrolysis oil

The switchgrass and heavy oil were mixed in ratios of 2:1 and 1:1. A low pressure/low temperature, high pressure/low temperature and low pressure/high temperature case was investigated for both conditions. As shown in Table 2, the pellet densities were the highest recorded at over 950 kg/m<sup>3</sup>. Furthermore, at elevated temperatures with a grass/tar ratio of 2:1, the tensile strength was very high (1110 kPa), again, the highest recorded throughout the testing. The reason for the vast increase in pellet strength would be the combined result of the lignin present in the biomass plus the addition of the tar, which when softened inside the pelletiser, dispersed between the switchgrass fibres. Therefore, when left to cool, a more advantageous, desirable pellet was formed. The use of heavy pyrolysis oils would be especially beneficial if the raw biomass was in a pre-shredded form for example, sawdust and cutter shavings. The main pitfalls for using heavy pyrolysis oil as a binding agent would be operational and health issues involved with using the toxic, corrosive and highly viscous material. Further work should look into more detail at the minimum tar proportions necessary to maintain such quality pellets. The liquid phase from slow pyrolysis of biomass can range over 40% of the input material; however, after the separation of the aqueous phase, less than 15% remains as a heavy oil [13]. Therefore, minimum amounts of tar should ideally be used as the binder.

### 3.5. Straw pellets

After establishing a good set of results for switchgrass pellets, it was necessary to pelletise a different herbaceous crop, to observe the effects of lignin as a binding agent and to ensure the nature of the pelletisation was alike for a similar fuel. The raw straw samples arrived in cut form, slightly longer in length than the switchgrass, ranging between 10 mm and 150 mm. Four key straw cases were examined – 166 bar and 387 bar at room temperature and 166 bar at 75 °C and 95 °C. From the evaluation between the

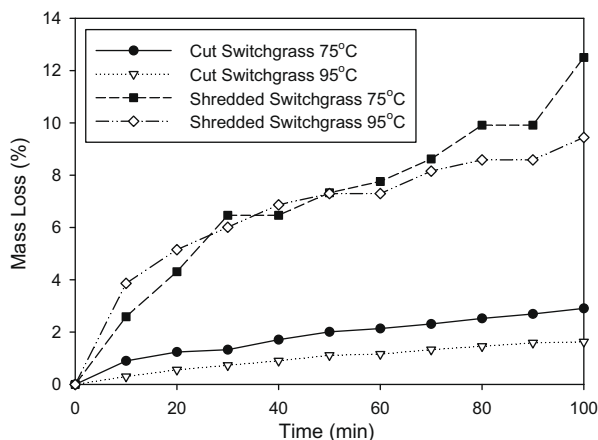


Fig. 8. Mass loss versus time during durability tests.

Table 2

Pellet properties for pellets of switch grass/tar mixture.

| Pelletisation conditions |                |                  | Pellet properties            |                        |
|--------------------------|----------------|------------------|------------------------------|------------------------|
| Grass/tar ratio          | Pressure (bar) | Temperature (°C) | Density (kg/m <sup>3</sup> ) | Tensile strength (kPa) |
| 2:1                      | 166            | 14               | 560                          | 90                     |
| 2:1                      | 552            | 14               | 756                          | 170                    |
| 2:1                      | 166            | 95               | 999                          | 1110                   |
| 1:1                      | 166            | 14               | 999                          | 350                    |
| 1:1                      | 552            | 14               | 1076                         | 600                    |

**Table 3**

Comparison of pellet properties between cut switchgrass and straw.

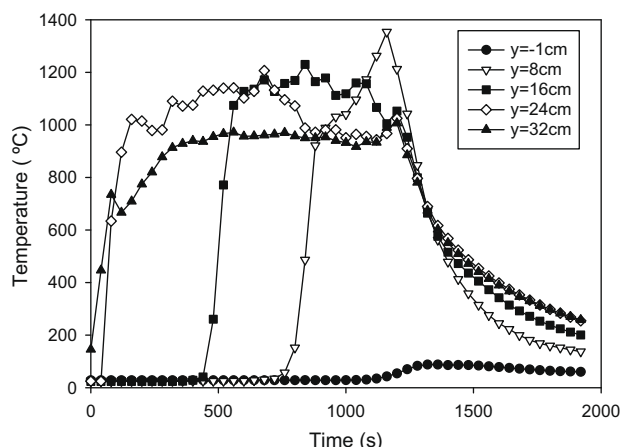
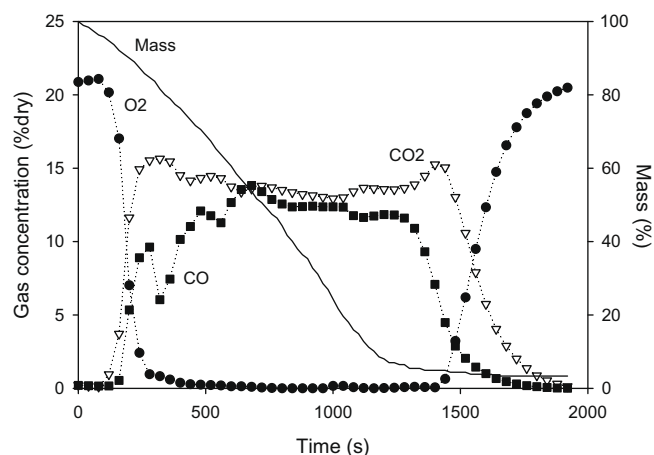
| Pelletisation conditions |                |                  | Pellet properties            |                        |
|--------------------------|----------------|------------------|------------------------------|------------------------|
| Material                 | Pressure (bar) | Temperature (°C) | Density (kg/m <sup>3</sup> ) | Tensile strength (kPa) |
| Switchgrass              | 41             | 14               | 505                          | 130                    |
| Straw                    | "              | "                | 461                          | 150                    |
| Switchgrass              | 95             | 14               | 736                          | 310                    |
| Straw                    | "              | "                | 656                          | 315                    |
| Switchgrass              | 41             | 75               | 763                          | 480                    |
| Straw                    | "              | "                | 785                          | 480                    |

switchgrass pellets and the straw pellets, there was found to be little variation among the results (Table 3). The densities and compressive strengths were very similar for each of the four scenarios. Further, both straw and switchgrass have a lignin content of about 17% [24]. Therefore, it was deduced that the lignin content was also not large enough to result in a noticeable difference in the quality of the pellets. The findings from the straw tests exemplified the fact that an increase in pressure resulted in an increase in pellet strength and the lignin present in the straw was still serving as an effective binding agent at elevated temperatures.

#### 4. Results and discussion: combustion test

Packed bed reactors are commonly applied to biomass combustion at various scales ranging from small stoves ( $\sim 10$  kW<sub>th</sub>) to large moving grate furnaces ( $\sim 10$  MW<sub>th</sub>). In the combustion test for the switchgrass pellets, very stable combustion was achieved at high temperatures with steady gas composition. Fig. 9 presents the temperature profiles of the bed that shows a continuous downward propagation of ignition front. After the ignition front reaches the grate at about  $t = 1100$  s, the oxidation of the remaining char led to further temperature increase to over 1200 °C near the grate ( $y = 8$  cm). In Fig. 10, the high CO concentration indicates that the combustion in the bed was highly fuel-rich. Therefore, the use of overfire air is essential in order to complete oxidation reactions.

Table 4 compares key combustion parameters between the pellets and the raw switchgrass at the tested air flow rate (936 kg/m<sup>2</sup> h). The burning rate is the rate of mass loss per unit cross-sectional area, which was calculated from the measured bed weight. The overall burning rate of the pellets (252 kg/m<sup>2</sup> h) in the test was similar to that for the grass which was found to be the maximum value achievable. While the burning rate of the raw switchgrass quickly dropped at higher air flow rates (e.g. 186 kg/m<sup>2</sup> h at

**Fig. 9.** Temperature profile for fixed bed combustion of switchgrass pellets.**Fig. 10.** Gas composition and mass loss for fixed bed combustion of switchgrass pellets.**Table 4**Comparison of key combustion characteristics for fixed bed combustion between switchgrass and its pellets at an air flow rate of 936 kg/m<sup>2</sup> h.

| Material                                       | Raw cut switchgrass pellets | Raw cut switchgrass [12] |
|------------------------------------------------|-----------------------------|--------------------------|
| Bulk density (kg/m <sup>3</sup> )              | 370                         | 57                       |
| Mass loss during IPS (%)                       | 90.0                        | 65.6                     |
| Burning rate during IPS (kg/m <sup>2</sup> hr) | 312                         | 385                      |
| Overall burning rate (kg/m <sup>2</sup> hr)    | 252                         | 253                      |

IPS: Ignition Propagation Stage.

1170 kg/m<sup>2</sup> h of air flow rate) [12], the pellets are expected to have increased burning rates. The larger and denser particles are more resistant to convective cooling, which can achieve high burning rates over a wider range of air flow rates. A recent study by Porteiro et al. [25] on combustion of different pellets shows that pellets maintained high ignition rates at air flow rates of 1400 kg/m<sup>2</sup> h ( $\sim 0.4$  kg/m<sup>2</sup> s) or higher. Additionally, more stable temperature profiles can be achieved for the pellets, since they are more homogeneous and less sensitive to changes in the air flow rate. Therefore, pelletisation is advantageous in terms of combustion characteristics in a packed bed. Further investigations are required for comprehensive combustion characteristics of the grass pellets.

#### 5. Conclusions

In pelletisation of herbaceous crops, the lignin present in the biomass softened at elevated temperatures and acted as a binding agent. DMTA tests for a switchgrass pellet showed that maximum potential softening occurred at 70 °C followed by an increase in pellet hardening due to moisture evaporation. Consequently, a pellet made at 166 bar and 75 °C was more durable and stronger than a pellet formed at 552 bar at room temperature. Future work should focus on the effect of moisture content in relation to the quality of the pellets produced.

Comparing the cut switchgrass pellets to the three remaining cases, the cut switchgrass produced more desirable pellets over shredded switchgrass due to additional binding effect of inter-twined fibres. The torrefaction of grass was not an attractive pre-process as the pellets were very brittle and possessed little mechanical strength and reduced bulk density. Heavy pyrolysis oil has a potential for use as binding material which can significantly increase the strength and durability of the pellets.

The combustion test in a fixed bed demonstrated that the switchgrass pellets could achieve very stable combustion at a high burning rate. At an air flow rate of 936 kg/m<sup>2</sup> h, the pellets had an overall burning rate of 252 kg/m<sup>2</sup> h, which was very close to the highest value observed for the raw grass. Further study is required to investigate the detailed combustion characteristics of the pellets.

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